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The Ultraviolet/optical Variability and Its Implication for X-ray and Line Emission in Quasars

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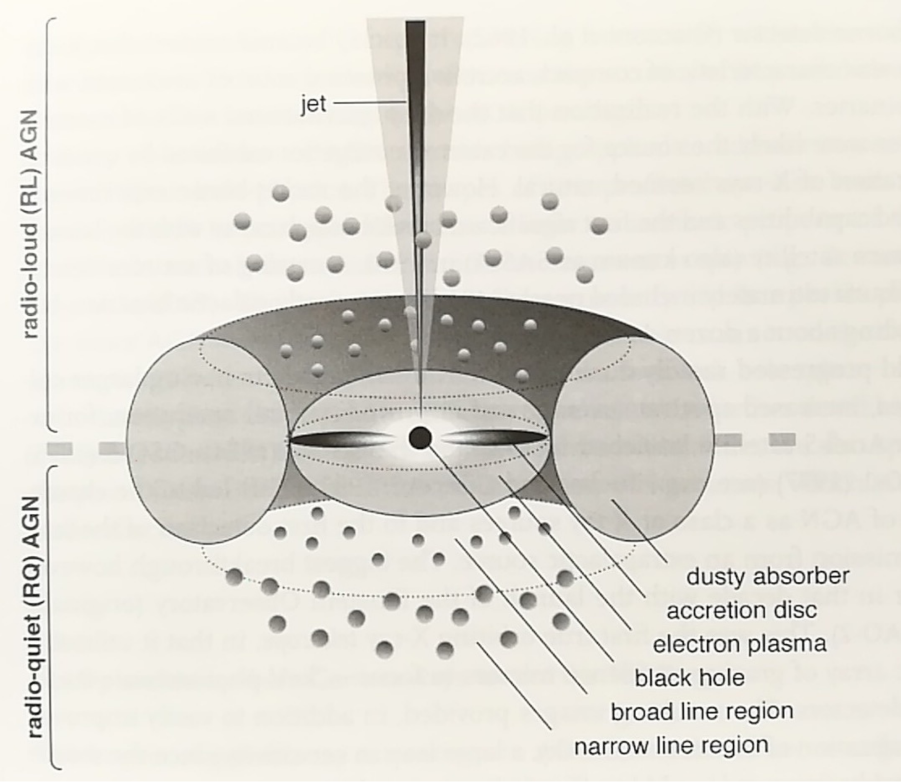
Multi-band Emission from AGN



disk	——>	UV/optical
corona	——>	X-ray
BLR	——>	broad line
NLR	——>	narrow line
torus	——>	IR
jet	——>	radio/X-ray

will vary over time

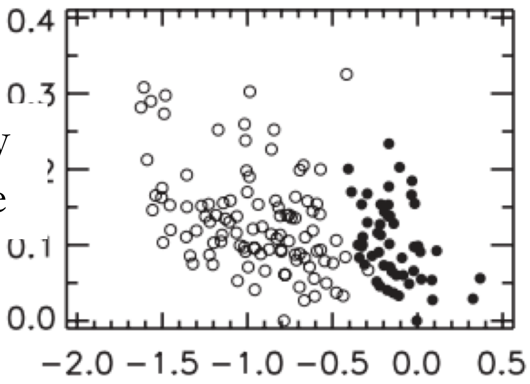
Beckmann+2012

Relation to other physical parameter

- Luminosity, Eddington ratio — negative (Berk+2004, Wilhite+2008, Ai+2010, Zuo+2012, Meusinger+2013)
- Black hole mass — slightly positive (Wilhite+2008, MacLeod+2010, Kozlowski+2016)
- wavelength — negative (Berk+2004, Wilhite+2005, Meusinger+2011, Zuo+2012)
- redshift — probably positive (Berk+2004)

probably negative (MacLeod+2010, Meusinger+2011)

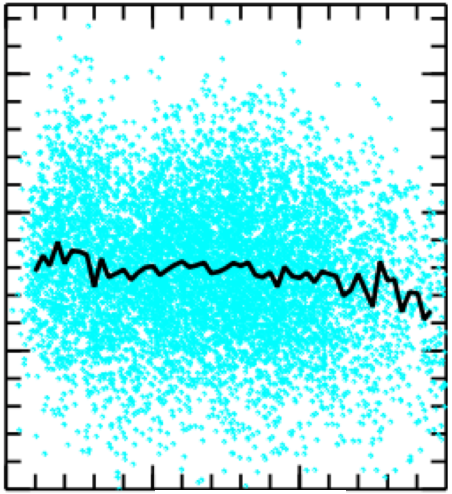
variability amplitude



Eddington ratio

Ai+2010

variability amplitude



redshift

Meusinger+2011

Relation to other physical parameter

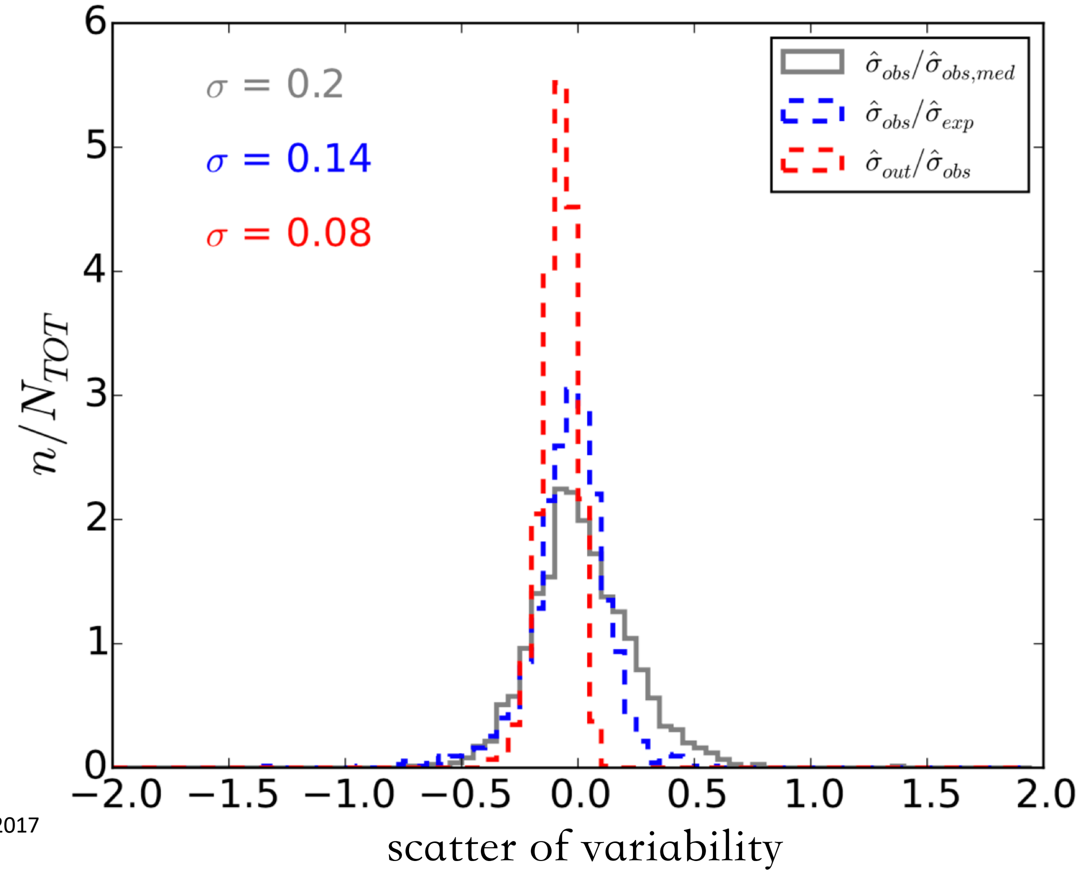
Grey: observational data

Blue: scatter from parameter

Red: scatter from fitting uncertainty

can't completely explain the scatter:

What physical processes are related with?



Guo+2017

Variability sample: SDSS S82, ~ 10-year light curves 9248 quasars (Macleod+2012)

L_{bol}, M_{bh}, z: SDSS DR7 Quasar Catalog (Shen+2011)

UV/Optical Variability Amplitude (Vaughan+2003):

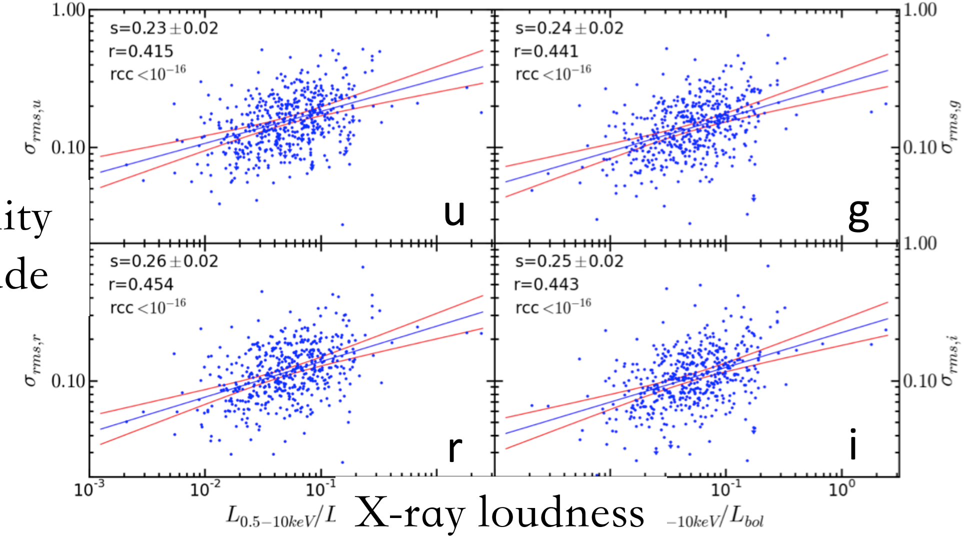
$$\sigma^2_{\rm rms} = \frac{1}{N-1}\sum(X_i - \bar{X})^2 - \frac{1}{N}\sum\sigma_i^2 \qquad {\rm err}(\sigma^2_{\rm rms}) = \sqrt{\frac{2}{N}} \times \frac{1}{N}\sum\sigma_i^2$$

Kang, Wen-Yong; Wang, Jun-Xian; Cai, Zhen-Yi; et al. APJ 868,58 (2018)

variability amplitude vs X-ray loudness

X-ray Loudness： $L_{0.5-10\ keV}/L_{bol}$ (catalog from Ananna+2017, final sample： 499)

variability amplitude

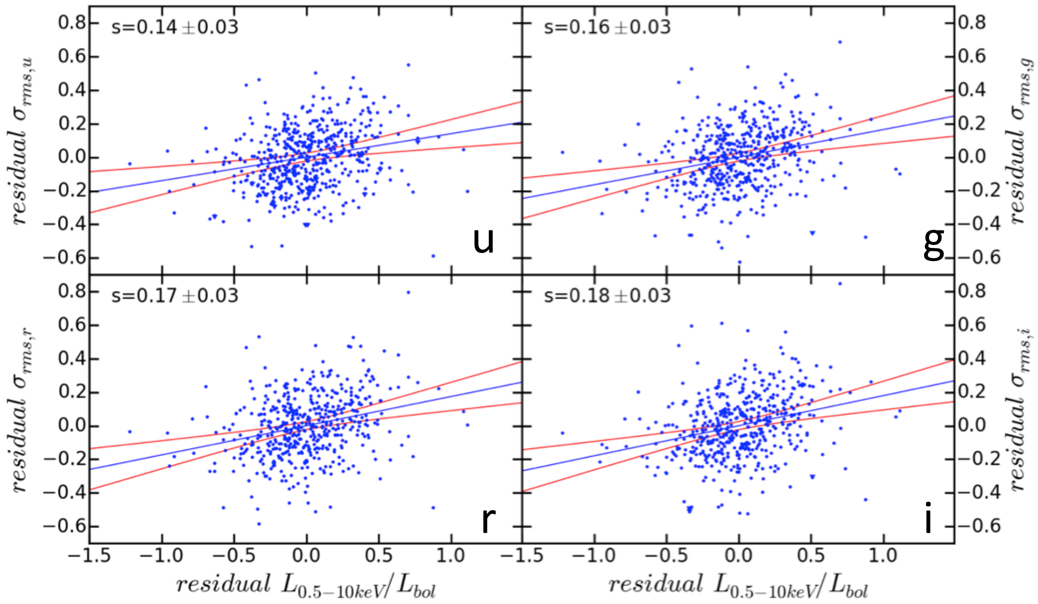


X-ray loudness

Significant positive correlation！ --> might be the secondary effect

Kang, Wen-Yong; Wang, Jun-Xian; Cai, Zhen-Yi; et al. APJ 868,58 (2018)

controlling effect of Eddington ratio, BH mass, redshift & RF wavelength



UV/Optical variability amplitude

vs

X-ray loudness :

intrinsic physical correlation

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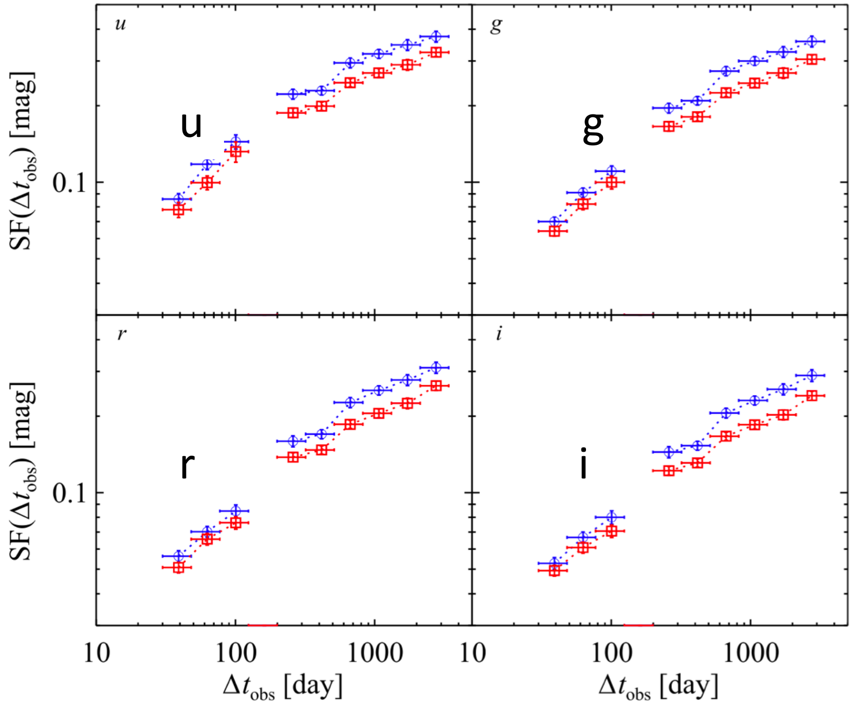
variability amplitude vs X-ray loudness



>200d： X-ray stronger sample is more variable than smaller sample

<200d： cannot be distinguished

X-ray reprocessing paradigm：timescale ~ days

inconsistent with this result

Kang, Wen-Yong; Wang, Jun-Xian; Cai, Zhen-Yi; et al. APJ 868,58 (2018)

σ_{rms} vs EW_{line} intrinsic correlation

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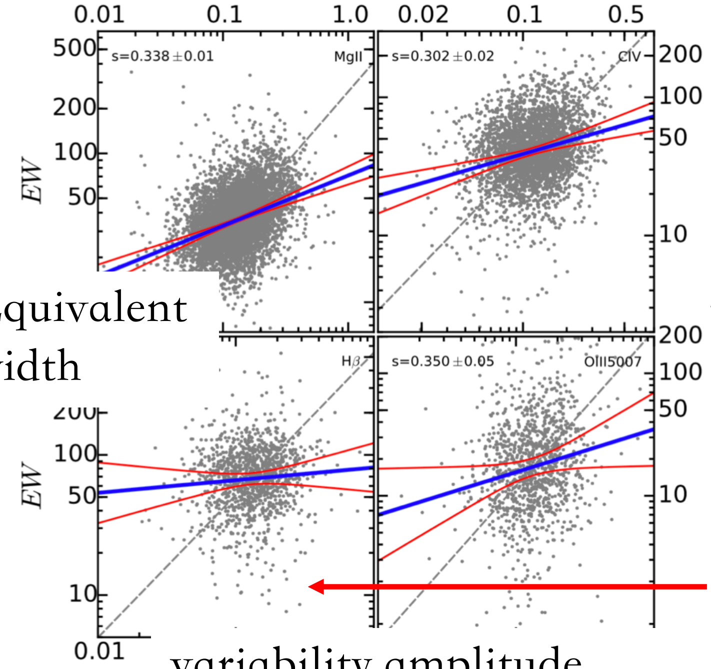
Emission Line: SDSS DR7 Quasar Catalog (Shen+2011)

- match sample:

EL	(number)
Mg II	(6553)
C IV	(3313)
H β	(1226)
[O III]5007	(1132)



Equivalent width

variability amplitude

Positive correlation!

(except H β)

Kang, Wen-Yong; Wang, Jun-Xian; Cai, Zhen-Yi; et al. APJ 911,148 (2021)

σ_{rms} vs EW_{line} intrinsic correlation

controlling the effect of Eddington ratio, BH mass, redshift

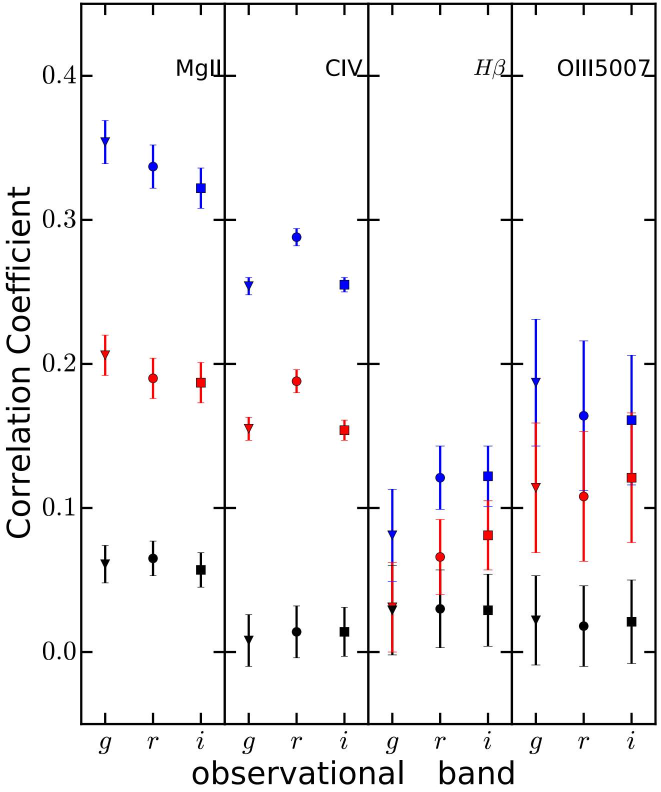
Blue: direct correlation

Red: intrinsic correlation

Black: artificial correlation from L_{bol}&M_{bh}

Result: σ_{rms} vs EW_{line} have intrinsic correlation

except Hβ



Kang, Wen-Yong; Wang, Jun-Xian; Cai, Zhen-Yi; et al. APJ 911,148 (2021)

Robustness of the correlation

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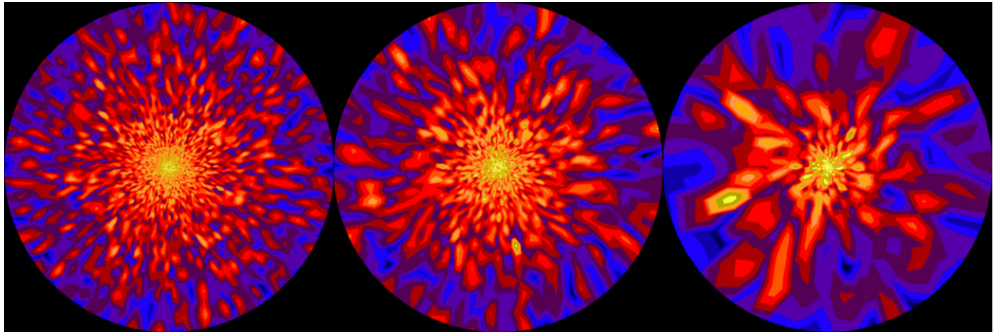
- incompleteness of X-ray detection
- incompleteness of EL
- detection uncertainties of L_{bol}, M_{bh}
- difference between X-ray bands
- effect from the most scattered sources
- single spectra observation vs multiple photometric observation

Won't change the result!

Inhomogeneous disk model



Dexter+2011
Ruan+2014
Cai+2016, 18, 20; see Cai's talk

- observation: magnetic turbulence->thermal fluctuation of disk->variability (Kelly+2009)
- stronger disk turbulence->more energy to corona->stronger X-ray emission
- timescale of turbulence propagation: ~ years (orbit timescale of disk, thermal timescale, CLQs observation timescale)

Kang, Wen-Yong; Wang, Jun-Xian; Cai, Zhen-Yi; et al. APJ 868,58 (2018)

Possible Explanation

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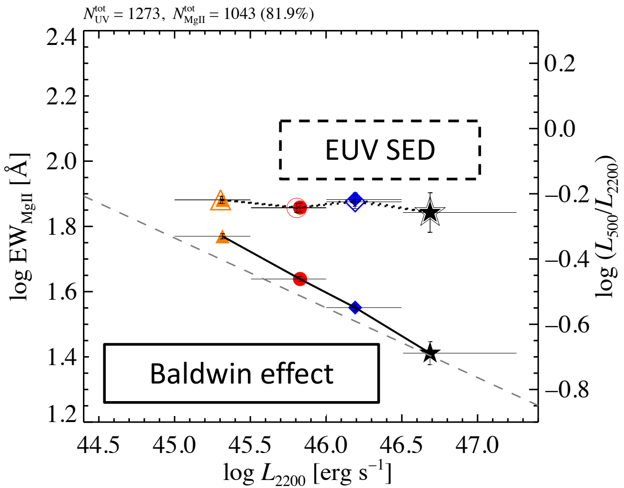
1. stronger magnetic turbulence->bluer/harder SED->stronger EL
2. stronger magnetic turbulence->stronger disk wind->larger covering factor

how to distinguish



Cai & Wang 2023, NA submitted

EUV SED is not the main driver

stronger disk wind

-> larger covering factor

Kang, Wen-Yong; Wang, Jun-Xian; Cai, Zhen-Yi; et al. APJ 911,148 (2021)

Summary

- UV/Optical variability has intrinsic positive correlation with X-ray intensity & equivalent width of emission lines

- corona heating:
  - stronger disk turbulence->more energy to corona->X-ray stronger

- production of cloud in line region:
  - stronger magnetic turbulence->stronger disk wind->larger covering factor

Thanks for your attention!

Appendix

Sample Selection

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variability sample:

SDSS S82, ~ 10-year light curves

9248 quasars (Macleod+2012)

radius < 0.7”

X-ray sample：

Stripe 82X, 31.3 deg^2

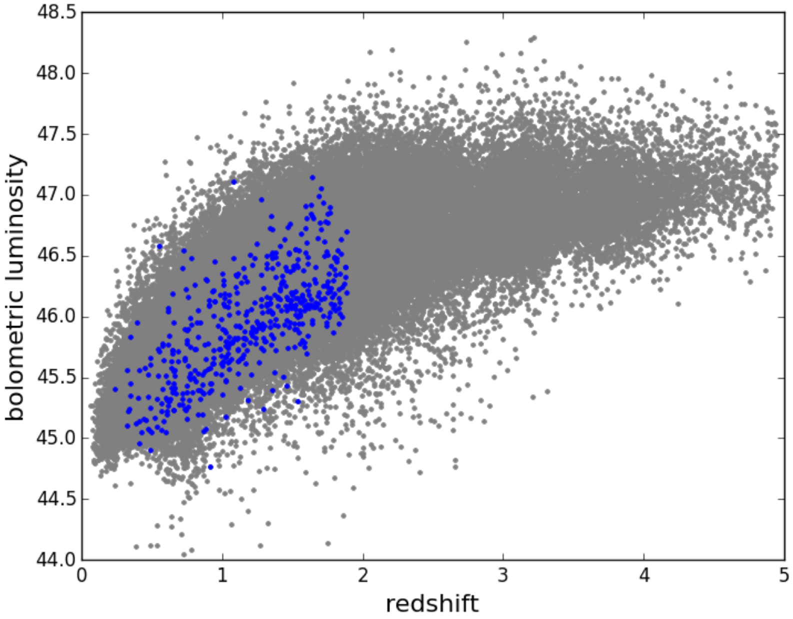
6181 X-ray sources (Ananna+2017)

dropped：

- z band
- photometric uncertainty > 0.2 mag
- observed number < 20
- redshift > 1.9

final sample： 499

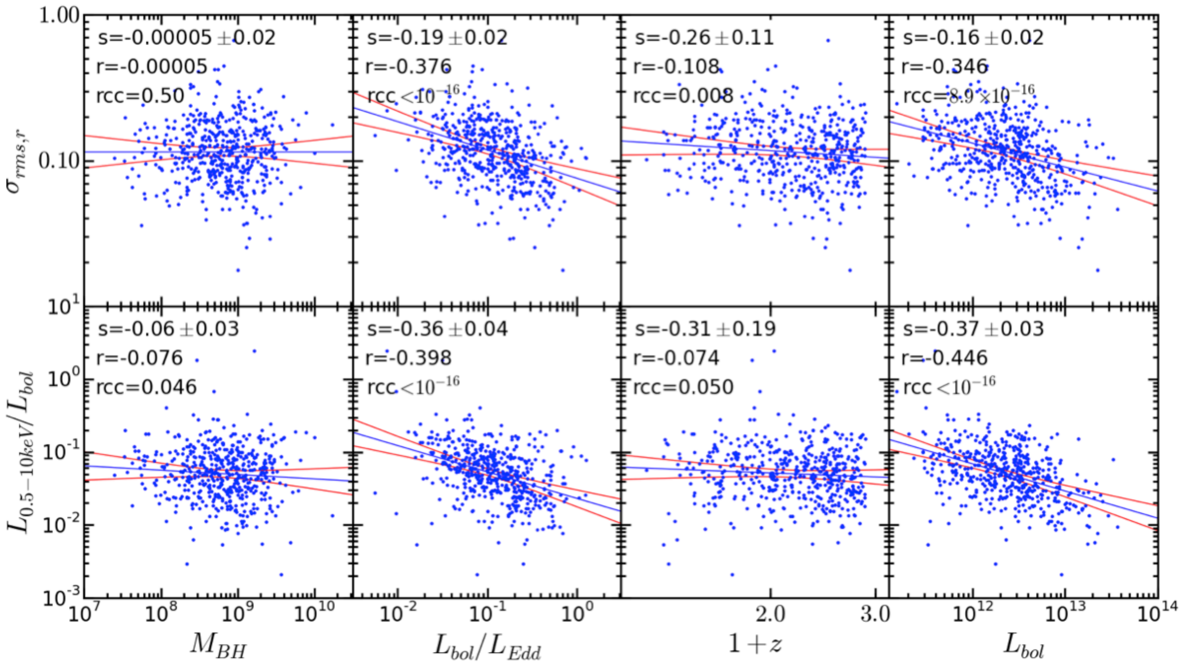
M_{bh}, L_{bol} , z from Shen+2011



variability amplitude, X-ray loudness vs other parameters

variability amplitude

X-ray loudness



controlling the effect -> partial correlation & multiple linear regression partial correlation

$$r = \frac{\sum_{i=1}^{n}(X_{1i} - \bar{X}_1)(X_{2i} - \bar{X}_2)}{[(X_{1i} - \bar{X}_1)^2(X_{2i} - \bar{X}_2)^2]^{1/2}}$$

$$R = \begin{pmatrix} r_{1,1} & r_{1,2} & \cdots & r_{1,p} \\ r_{2,1} & r_{2,2} & \cdots & r_{2,p} \\ \vdots & \vdots & & \vdots \\ r_{p,1} & r_{p,2} & \cdots & r_{p,p} \end{pmatrix}$$

correlation coefficient: $r_{12.(3\ldots p)} = R_{12}/\sqrt{R_{11}R_{22}}$

significance level: $\mathrm{t}_{n-p}(rcc) = \sqrt{n-p}r/\sqrt{1-r^2}$

multiple linear regression

$$y = a_1x_1 + \cdots + a_px_p + a_0$$

controlling effect of Eddington ratio, BH mass, redshift & RF wavelength

Table 1. Partial correlation coefficients and multiple linear regression slopes between σ_{rms} and other physical parameters

σ_{rms}	r	rcc	$\dot{m}$ (a)	M (b)	1+z (c)	λ_c (d)	L_X/L_{bol} (s)	X-ray band
u	0.230	1.4×10^{-7}	-0.20±0.03	-0.09±0.03	0.15±0.14		0.13±0.02	soft
g	0.276	2.5×10^{-10}	-0.18±0.03	-0.06±0.03	0.28±0.14		0.16±0.02	
r	0.283	8.7×10^{-11}	-0.18±0.03	-0.07±0.03	0.11±0.14		0.17±0.02	
i	0.290	3.2×10^{-11}	-0.16±0.03	-0.05±0.03	-0.06±0.14		0.17±0.02	
u+g+r+i	0.269	$< 10^{-16}$	-0.18±0.02	-0.07±0.02	-0.42±0.08	-0.54±0.03	0.16±0.01	
u	0.180	3.1×10^{-4}	-0.19±0.04	-0.10±0.04	0.20±0.17		0.11±0.03	hard
g	0.227	7.2×10^{-6}	-0.18±0.04	-0.07±0.04	0.28±0.16		0.14±0.03	
r	0.262	2.6×10^{-7}	-0.16±0.04	-0.07±0.04	0.04±0.17		0.17±0.03	
i	0.279	4.2×10^{-8}	-0.12±0.04	-0.04±0.04	-0.12±0.17		0.18±0.03	
u+g+r+i	0.237	$< 10^{-16}$	-0.16±0.02	-0.07±0.02	-0.44±0.09	-0.55±0.04	0.15±0.02	
u	0.229	1.3×10^{-7}	-0.20±0.03	-0.09±0.03	0.16±0.14		0.14±0.03	full
g	0.270	4.6×10^{-10}	-0.18±0.03	-0.07±0.03	0.30±0.14		0.16±0.03	
r	0.280	1.0×10^{-10}	-0.18±0.03	-0.08±0.03	0.12±0.14		0.17±0.03	
i	0.285	4.9×10^{-11}	-0.15±0.03	-0.06±0.03	-0.04±0.14		0.18±0.03	
u+g+r+i	0.266	$< 10^{-16}$	-0.18±0.02	-0.07±0.02	-0.40±0.08	-0.54±0.03	0.16±0.01	

This table lists the best-f ultiple l r regression slopes of Equation 4 (for band u, g, r, and i), and of Equa n 7 (for $u+g+r+i$). Here r and rcc represent Spearm s correla n coefficient and significance level of the intrinsic correlation between ms and L_X/L_{bol} (controlling the effects o er para ers).

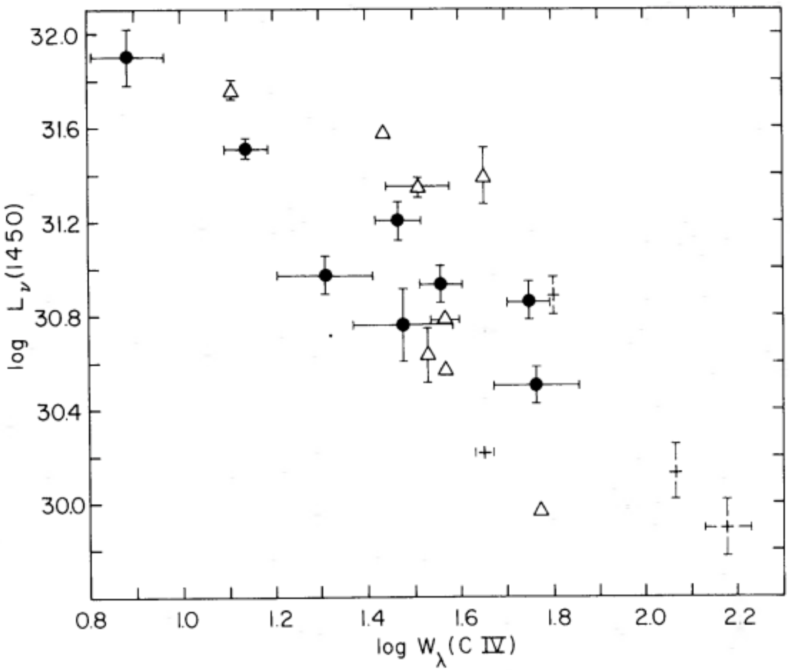
partial correlation

positive! reliable!

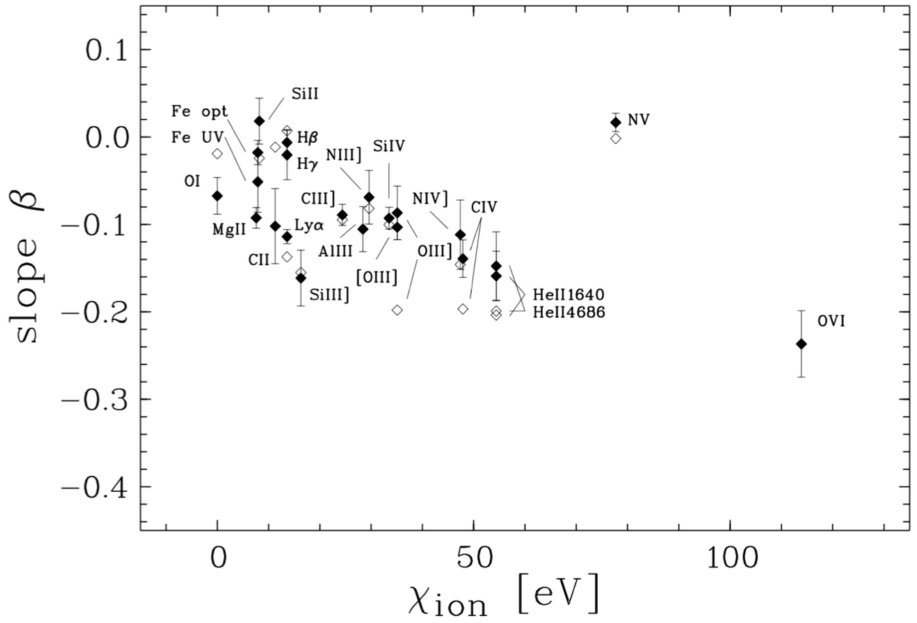
slope of multiple linear regression

>3σ positive correlation

anti-correlation between EW and continuum luminosity



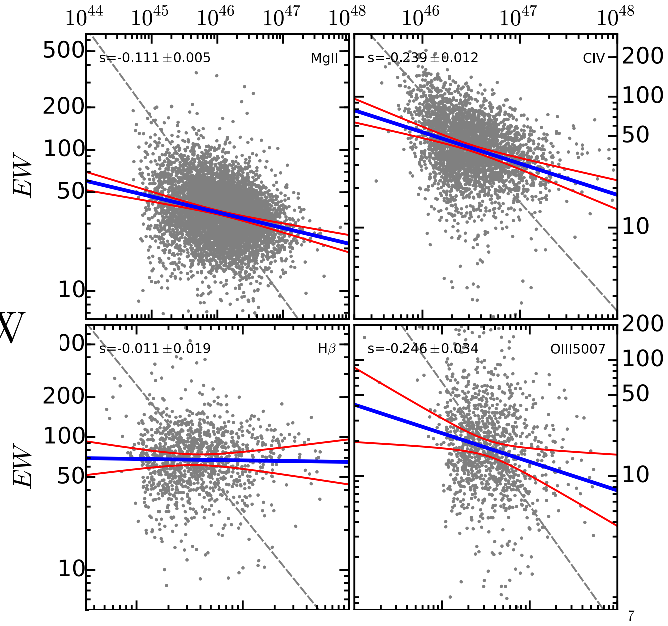
Baldwin 1977



Dietrich+2002

EW, variability amplitude vs luminosity

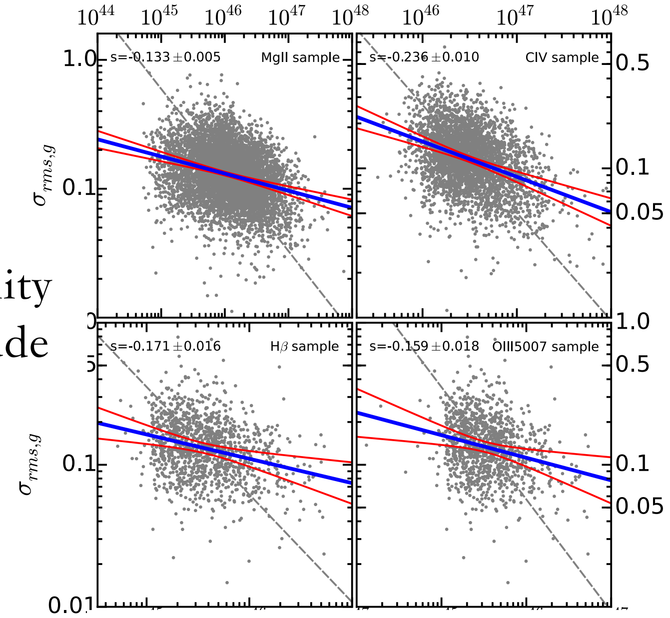
EW



bolometric luminosity

Baldwin Effect(except H β)

variability amplitude



bolometric luminosity

anti-correlation (consistent with previous result)

Robustness of the correlation

Stripe 82： 290 deg^2， 6306； Stripe 82X： 31.3 deg^2， 499.

X-ray detection completeness： 499 / (31.3 * 6306/290) = 73%

$$X_{simu} = X_{exp} + Gau[0, \sigma(residual\ X)]$$

original sample(n = 499)

	coefficient	significance level
real	~ 0.27	10^{-10}
simu	~ 0.002	0.5

dropped the most dimmed 27% X-ray sources sample(n = 364)

	coefficient	significance level
real	~ 0.27	10^{-10}
simu	~ 0.002	0.5

Don’t affect the result!

Robustness of the correlation

large detection uncertainties of L_{bol}, M_{bh}

random fluctuations to L_{bol}, M_{bh} :

$$L_{bol,\,simu} = L_{bol} + Gau(0, \sqrt{0.08^2 + \sigma_{L_{bol}}^2}) \qquad M_{bh,\,simu} = M_{bh} + Gau(0, \sqrt{0.4^2 + \sigma_{M_{bh}}^2})$$

0.08(Richards+2006), 0.4(Shen+2011) are calibration uncertainties.

correlation coefficient (significance level): real : ~0.27 (10^{-10})
simu : ~0.005 (0.4)

can't be attribute to observational uncertainties!

the correlation of hard band (2-10 keV) are slightly smaller

new sample: both soft & hard bands

$\sigma_{\rm rms}$ VS $L_{0.5-2\ keV}/L_{2-10 keV}$

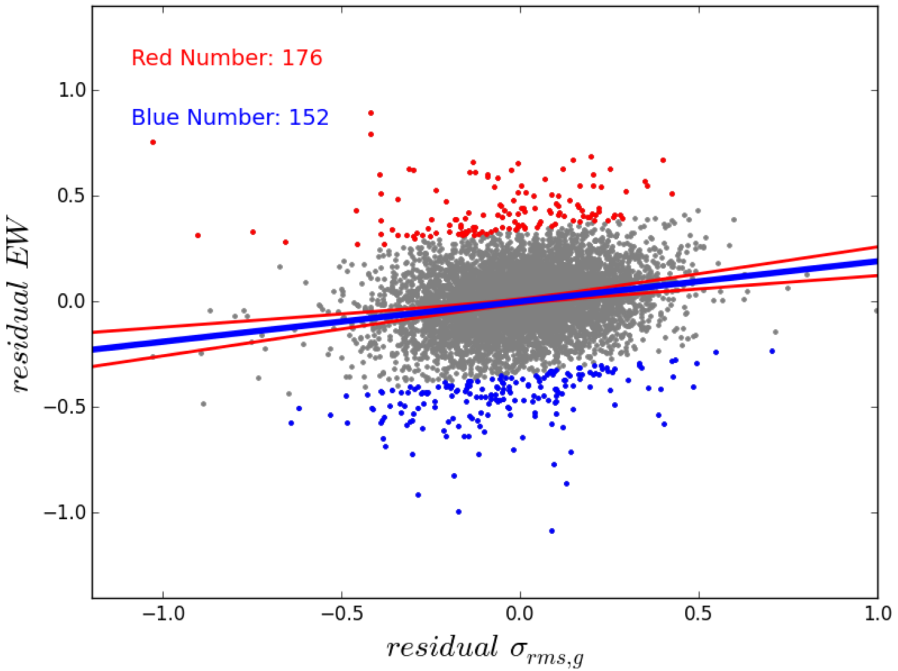
correlation coefficient (significance level): ~0.070 (0.1)

Difference between X-ray bands don't affect the result!

the most deviation of 5%: red & blue

subsample vs total:

$\frac{L_{bol}}{L_{Edd}}$、M_{bh}、$FWHM$ same distribution



removing this 5% gives consistent result

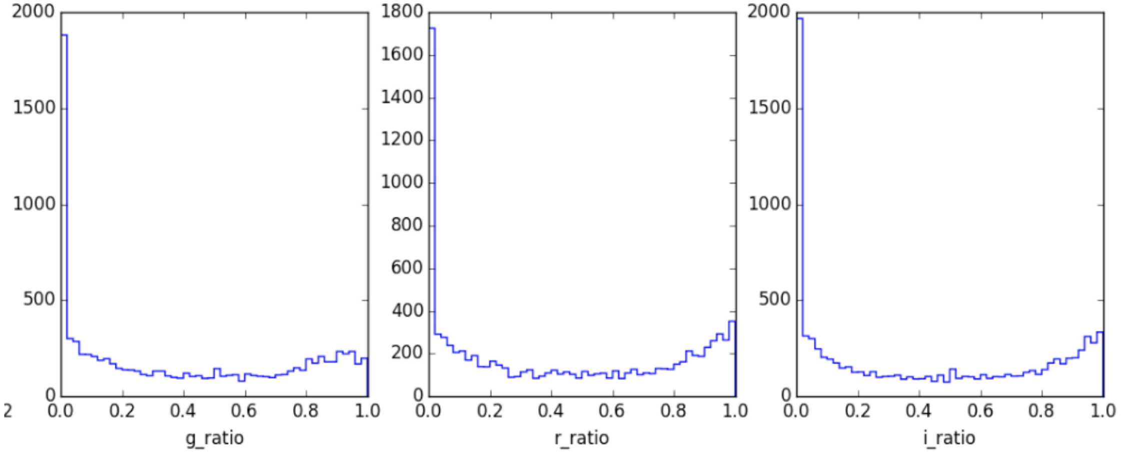
don't affect the result

- single spectra observation

vs

multiple photometric observation

ratio： $\frac{n(photometry\ fainter\ than\ spectra)}{n(total\ photometry)}$



photometry fainter than spectra： 15% -> fiber drop （about 10% ）

removing these sources：

- ratio distribute symmetric： The spectra can represent observations of quasars at random time
- The results of remaining sources are consistent with the overall

slightly correlation in Hβ

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Hβ: σ_{rms} vs EW_{line} slightly intrinsic correlation

no global Baldwin effect (Kang+2021, Sergeev+1999, Dietrich+2002, et al)

possibly relative to the complex physical processes of Balmer line:
The special nature of the electron transition, the difference in the cloud environment(Netzer+1995, Dietrich+2002, Netzer+2020)

need more studies